A Summary of MTP Results for PREDICT

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Introduction

We summarize in this document, the results of the analysis of the Microwave Temperature Profiler (MTP) data obtained on the NSF/NCAR GV (NGV) during the PREDICT field campaign. Its purpose is two-fold: to present the final MTP data with comments on each flight, and to discuss the excellent temperature calibration that was achieved. This document can be found under 'Documentation' in the data archive for the PREDICT MTP dataset so that users can obtain a summary of data quality and interesting features associated with each flight. Following this summary, we provide information on how the temperature was calibrated for the PREDICT campaign. It can be safely said that the PREDICT MTP data is the highest quality MTP data ever measured, and the temperature calibration is the best ever achieved. The only hiccup in the MTP data set is that on several flights the MTP frequency synthesizer, which normally tunes to three frequencies, would get stuck on a single frequency. In these cases, single frequency retrievals were performed and interspersed with the three frequency retrievals in the final archived data so that no data would be lost.

1 Results

Comments on the PREDICT MTP Final Data

Color-coded temperature curtain (CTC) plots are available for each of the PREDICT research flights with comments which include summaries of each flight. These comments may indicate areas of reduced data quality and/or significant features noted in the temperature profiles. These comments are important because the rapid ascents and descents of the GV during the HIPPO campaigns degrade the quality of the MTP retrievals. On the other hand, this profiling – as will be discussed below – allowed very accurate temperature calibration.

First we provide an elaboration on the impact of rapid ascents and descents on the quality of the MTP retrievals. When retrievals are performed, the retrieval coefficients that we use assume that the pressure altitude is approximately constant. Clearly over an ~20 second MTP scan, this is not the case. Given a typical ascent or descent rate of ~150 m/s, 3 km are traversed in the vertical. (The actual distance is more like 2 km because not all of the 20 seconds is needed for measurements, but this is still unacceptably large.) We have tried to save as much of the ascent and descent data as possible by changing the editing threshold when it appears that the retrievals are consistent with the short level flight segments. This can be done by examining the behaviour of the tropopause or the temperature field retrievals during ascent or descent compared to those during the level flight segments.

On each of the following CTC plots the x-axis is the Universal Time (UT) in kilo-seconds (ks), the left y-axis is the pressure altitude in kilometers (km), and the right y-axis is the pressure altitude in thousands of feet (kft). On the right is the color-coded temperature scale, which ranges from 170- 320 K. Also shown on each plot is the GV's altitude (black trace), the tropopause altitude (white trace), and a quality metric (gray trace at the bottom). The quality metric, which we call the MRI, ranges from 0 to 2 on the left pressure altitude scale. If the MRI is < 1, we consider the retrieval to be reliable; if it is > 1 the retrieval is less reliable, and users should contact us as to whether is can be used or not. With the exception of one flight (RF-02), all the MTP final data have been edited to include retrievals with the MRI< 1. If this excludes a specific time period that someone is interested in, they should contact us to see whether we can salvage that time period.

For most of the flights the CTC plots (which in fact are plotted using the archived data) are restricted to ± 8 km from flight level. On a few flights this was increased so that higher tropopauses could be plotted; this was the case for several tropical flights.

1.1 Test Flights

1.1.1 TF01

Local test flight from RMMA on August 3, 2010.

1.1.2 TF02

Local test flight from RMMA on August 4, 2010

1.1.3 TF03

Local test flight from RMMA on August 6, 2010

1.2 FF01

Ferry flight from RMMA to St. Croix (Figure 1).

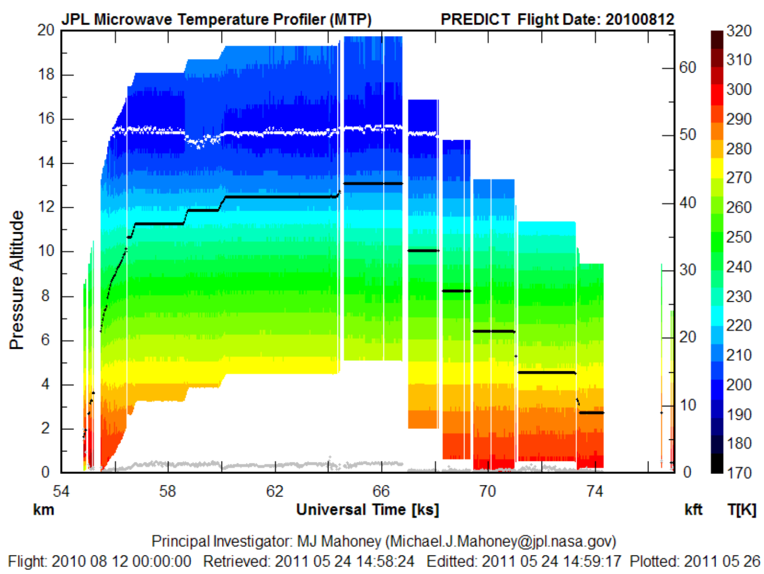


Figure 1: CTC Plot from Ferry Flight 1 on August 12, 2010

1.3 RF01

St Croix local flight (Figure 2).

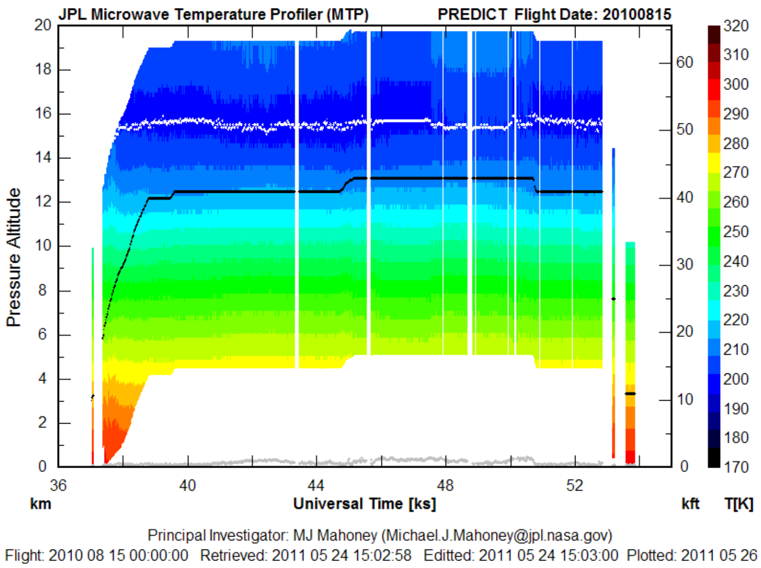


Figure 2: CTC Plot from Research Flight 1 on August 15, 2010

1.4 RF02

St Croix local flight

Frequency collapse to Ch2 at 40.0 ks. Did single channel retrieval for entire flight (Figure 3).

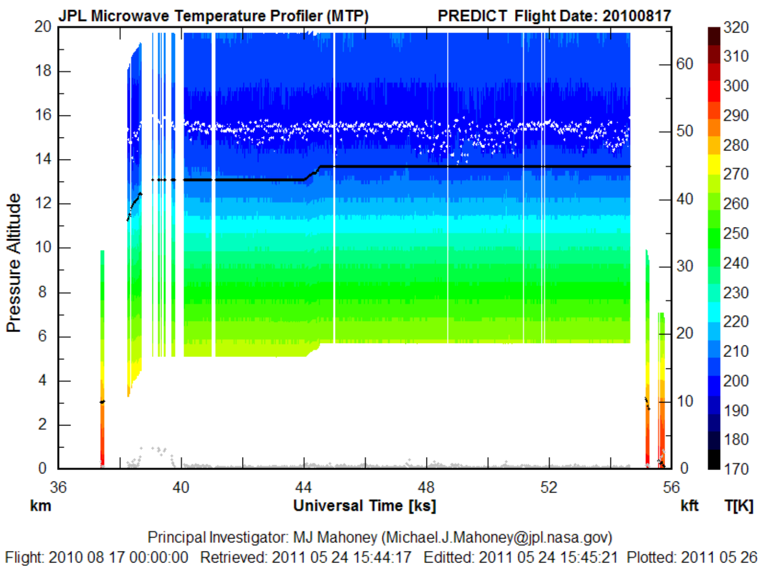


Figure 3: CTC Plot from Research Flight 2 on August 17, 2010

1.5 RF03

St Croix local flight (Figure 4).

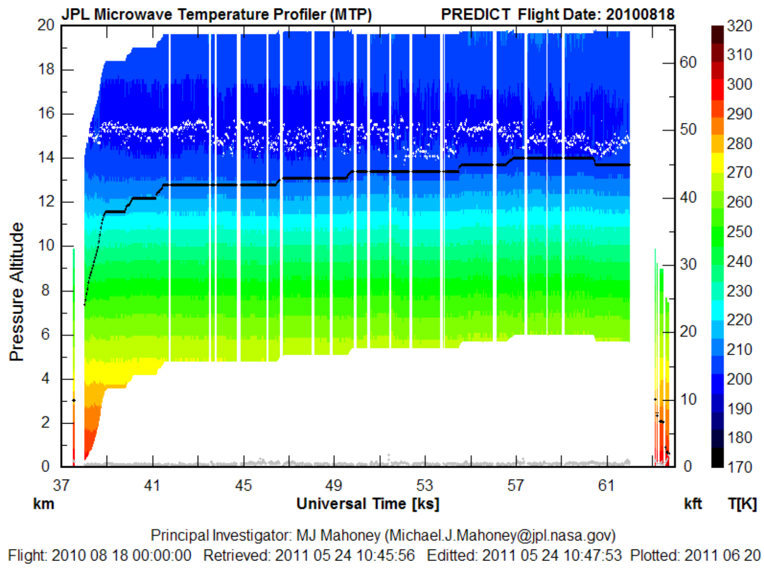


Figure 4: CTC Plot from Research Flight 3 on August 18, 2010

1.6 RF04

St Croix local flight

Frequency collapse to Ch3 at start of flight. Did single channel retrieval for entire flight (Figure 5).

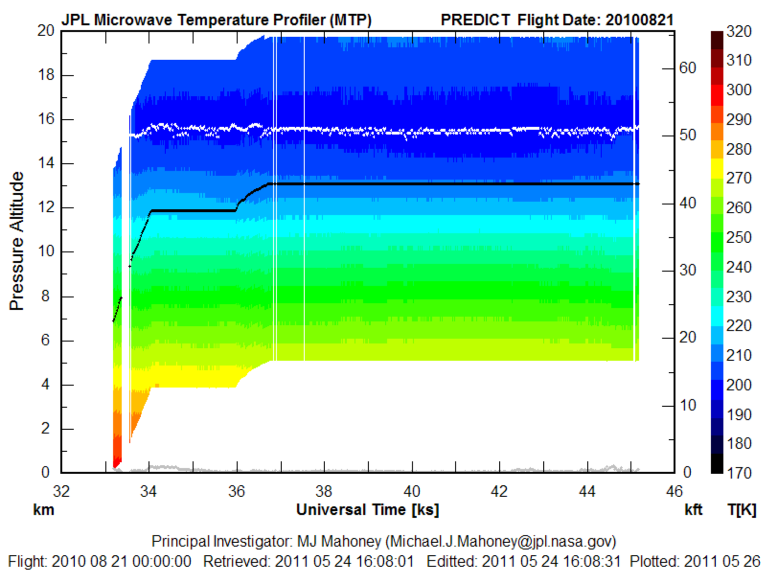


Figure 5: CTC Plot from Research Flight 4 on August 21, 2010

1.7 RF05

St Croix local flight

Frequency collapse to Ch2 at start of flight. Did single channel retrieval for entire flight (Figure 6).

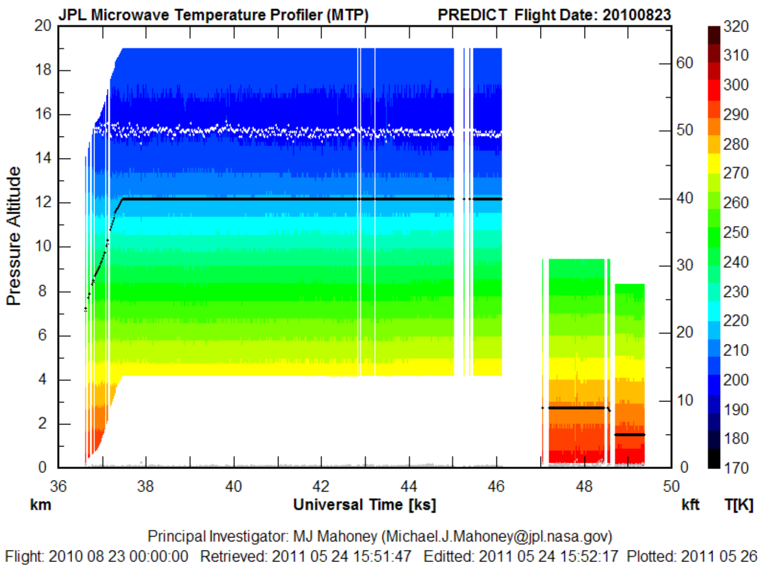


Figure 6: CTC Plot from Research Flight 5 on August 23, 2010

1.8 FF02

Ferry flight to Barbados on August 29, 2010

1.9 RF06

Barbados local flight (Figure 7).

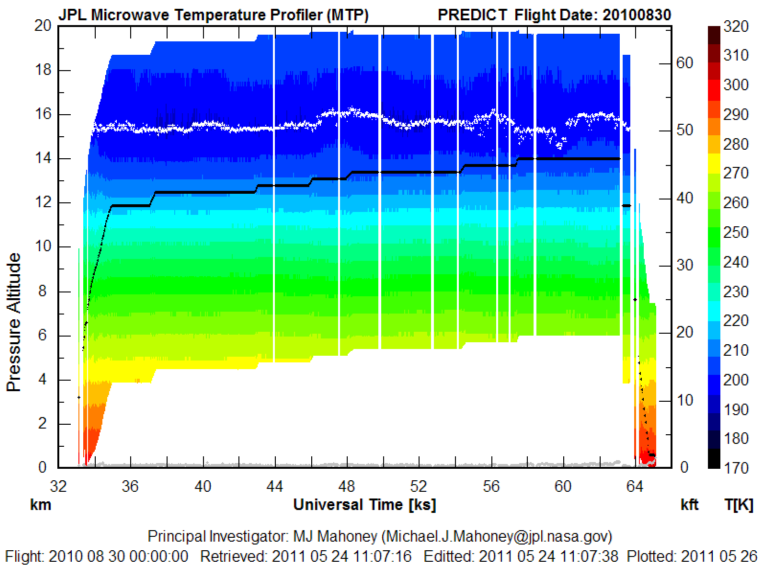


Figure 7: CTC Plot from Research Flight 6 on August 30, 2010

1.10 RF07

Barbados local flight (Figure 8).

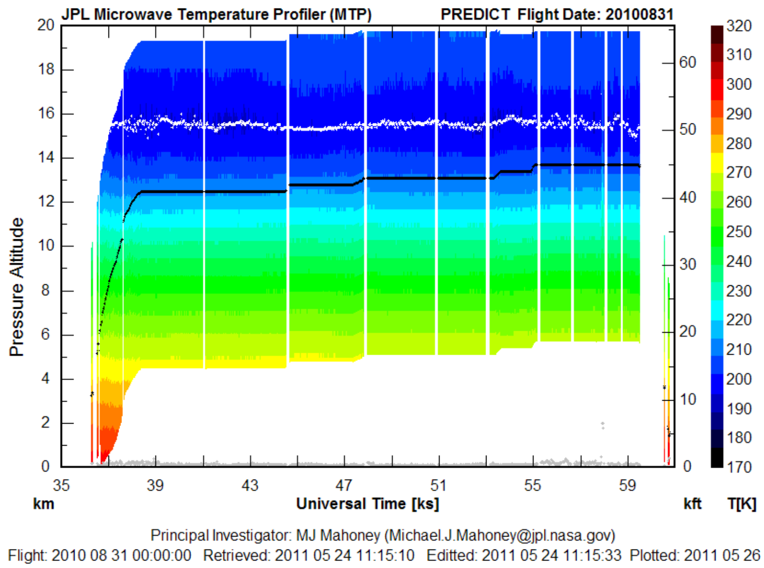


Figure 8: CTC Plot from Research Flight 7 on August 31, 2010

1.11 RF08

Barbados to St Croix

Frequency collapse to Ch3 from 54.7 - 57.3 ks. Did single channel retrieval during this period (Figure 9).

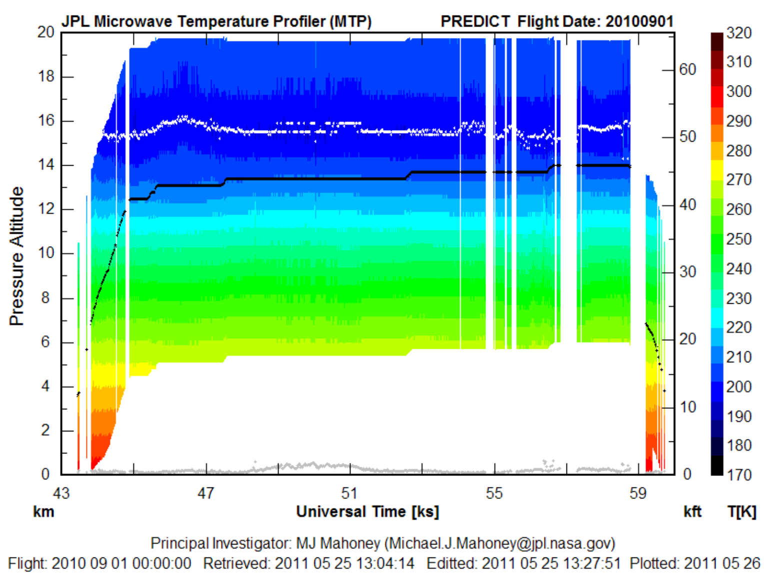


Figure 9: CTC Plot from Research Flight 8 on September 1, 2010

1.12 RF09

St Croix local flight (Figure 10).

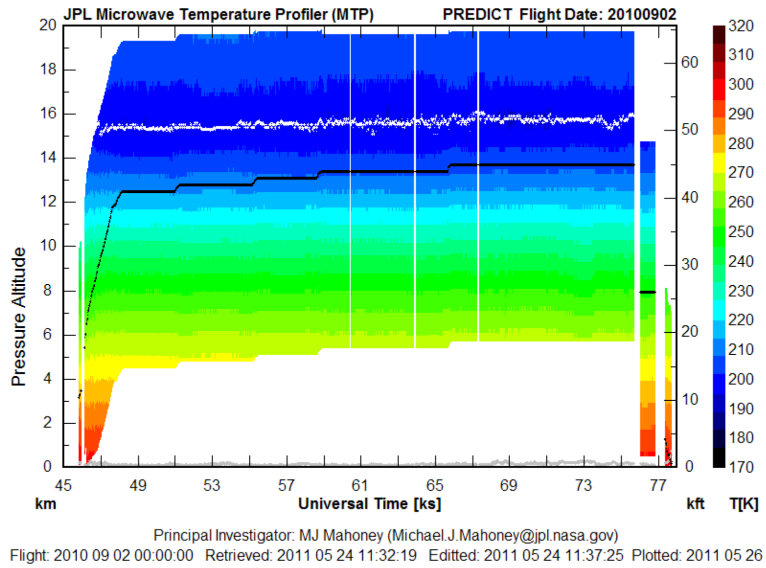


Figure 10: CTC Plot from Research Flight 9 on September 2, 2010

1.13 RF10

St Croix local flight(Figure 11).

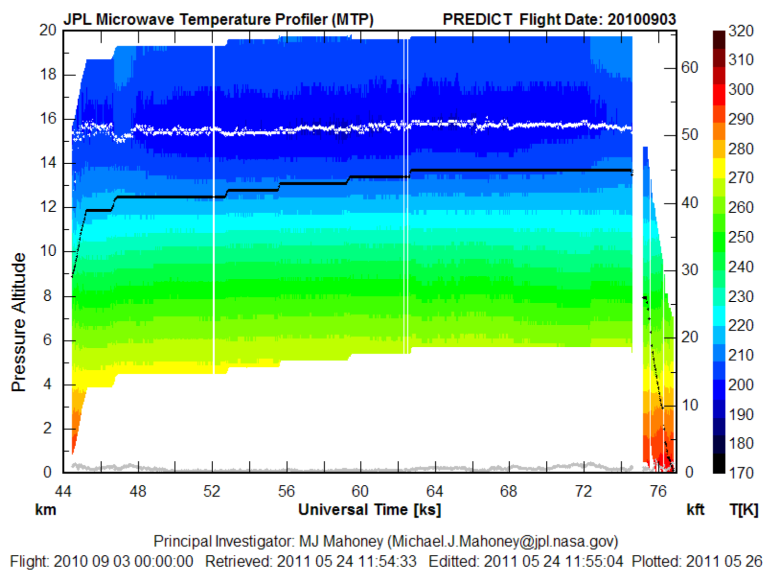


Figure 11: CTC Plot from Research Flight 10 on September 3, 2010

1.14 RF11

St Croix local flight (Figure 12).

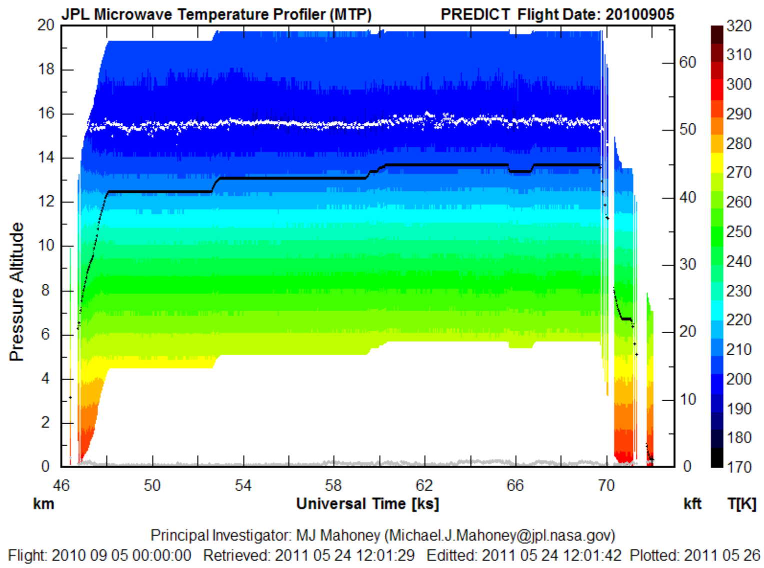


Figure 12: CTC Plot from Research Flight 11 on September 5, 2010

1.15 RF12

St Croix local flight (Figure 13).

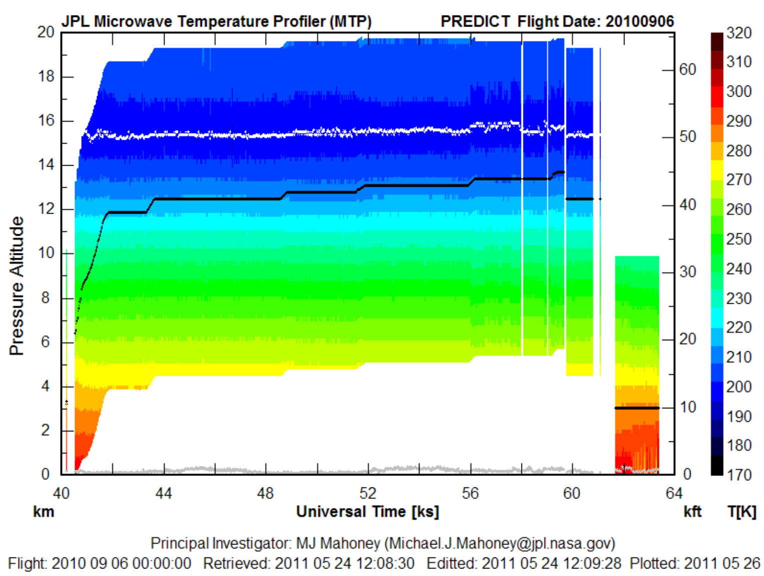


Figure 13: CTC Plot from Research Flight 12 on September 6, 2010

1.16 RF13

Ferry flight to Barbados on September 7, 2010 (MTP not on GV)

1.17 FF03

Ferry flight Barbados to St Croix (also MTP ground test) on September 8, 2010

1.18 RF14

St Croix local flight (Figure 14).

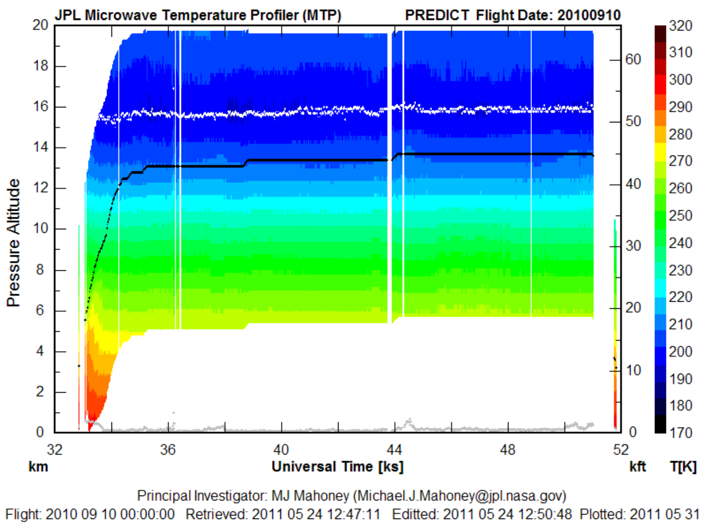


Figure 14: CTC Plot from Research Flight 14 on September 10, 2010

1.19 RF15

St Croix local flight (Figure 15).

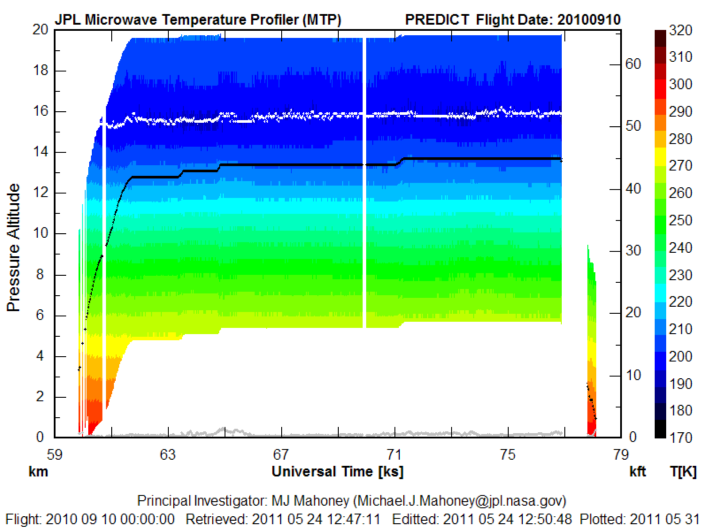


Figure 15: CTC Plot from Research Flight 15 on September 10, 2010

1.20 RF16

St Croix local flight (Figure 16).

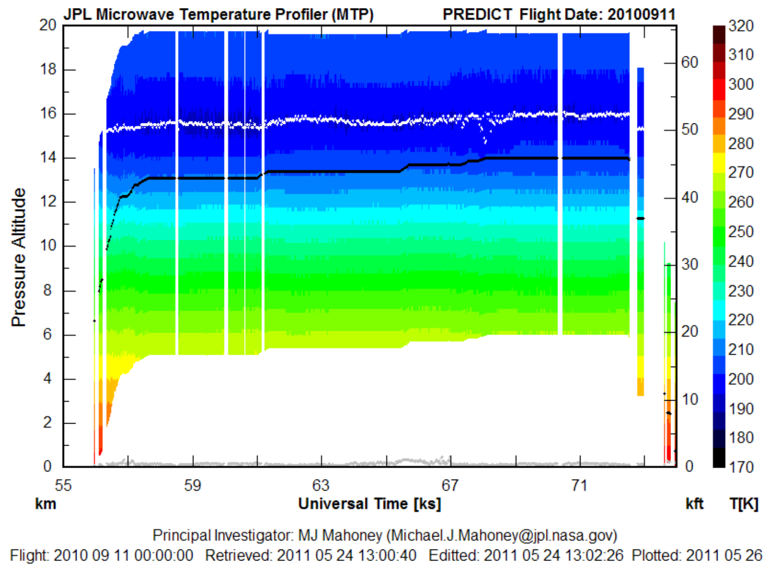


Figure 16: CTC Plot from Research Flight 16 on September 11, 2010

1.21 RF17

St Croix local flight (Figure 17). MTP thought to be overheating at ~43 ks and was turned off for an hour

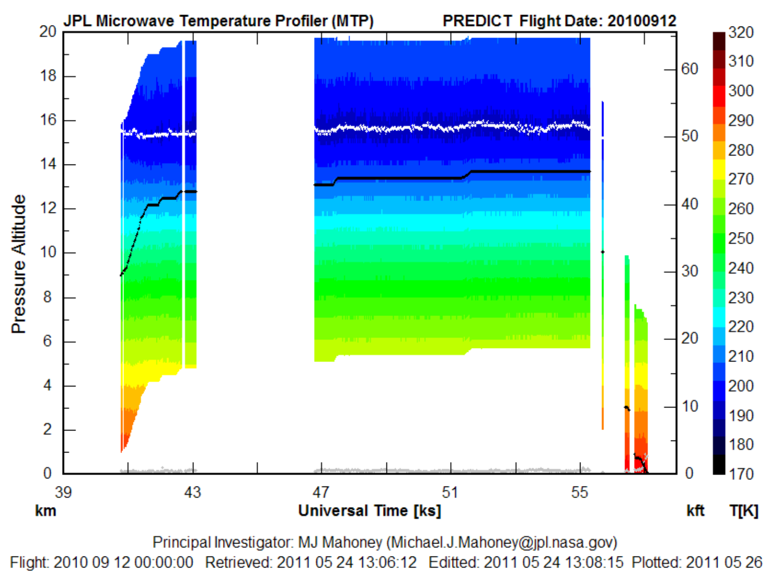


Figure 17: CTC Plot from Research Flight 17 on September 12, 2010

1.22 RF18

St Croix local flight (Figure 18). Frequency collapse to Ch2 from 41.9 - 46.8 ks. Did single channel retrieval during this period.

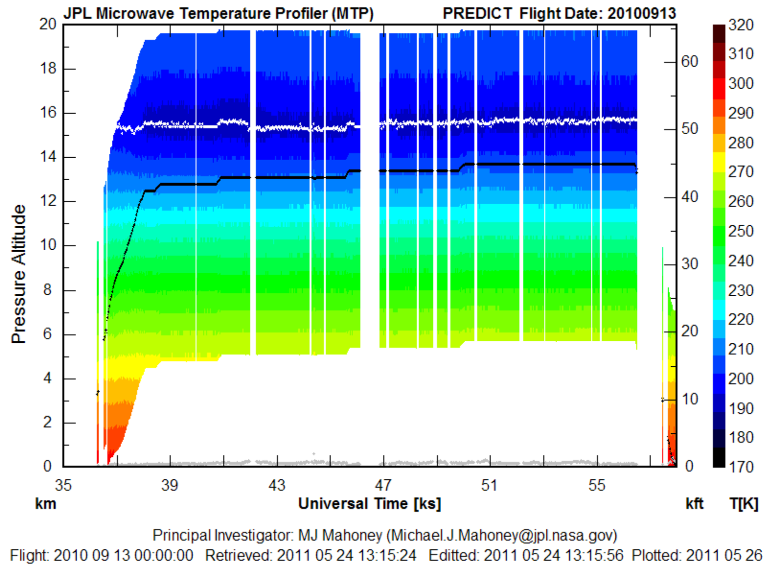


Figure 18: CTC Plot from Research Flight 18 on September 13, 2010

1.23 RF19

St Croix local flight (Figure 19).

-Frequency collapse to Ch1 from 54.8 - 56.7 ks. Did single channel retrieval during this period.
-Frequency collapse to Ch3 from 59.3 - 61.5 ks. Did single channel retrieval during this period.
-Frequency collapse to Ch3 from 63.2 - 64.8 ks. Did single channel retrieval during this period.

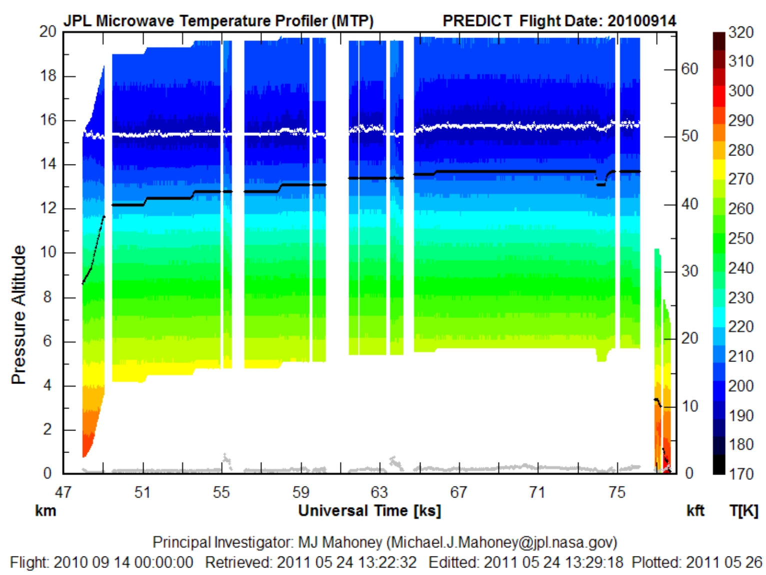


Figure 19: CTC Plot from Research Flight 19 on September 14, 2010

1.24 RF20

St Croix local flight (Figure 20).

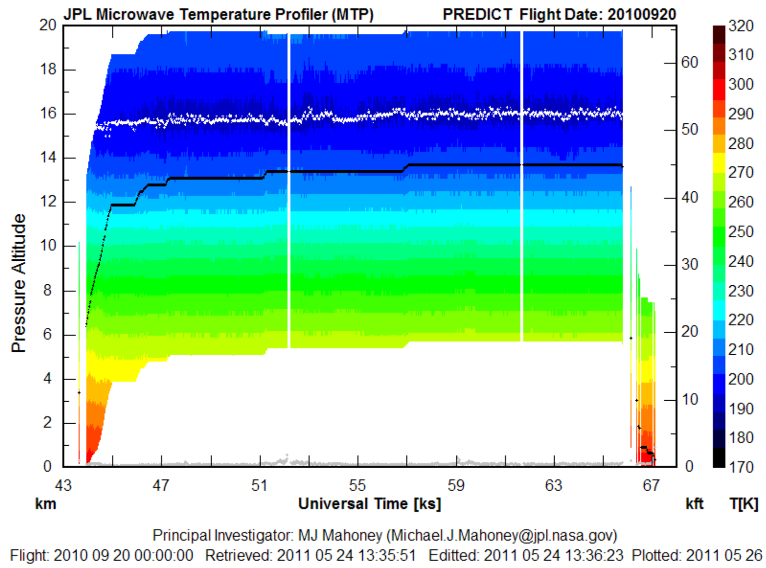


Figure 20: CTC Plot from Research Flight 20 on September 20, 2010

1.25 RF21

St Croix local flight (Figure 21).

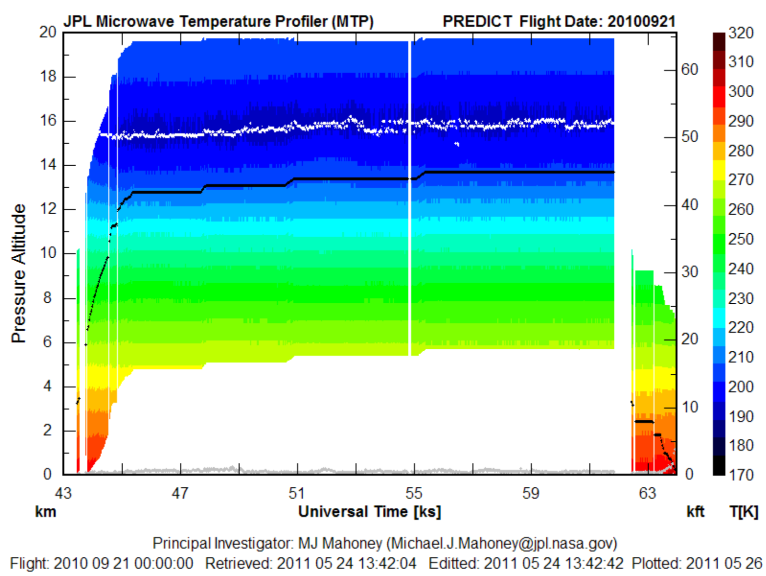


Figure 21: CTC Plot from Research Flight 21 on September 21, 2010

1.26 RF22

St Croix local flight (Figure 22).

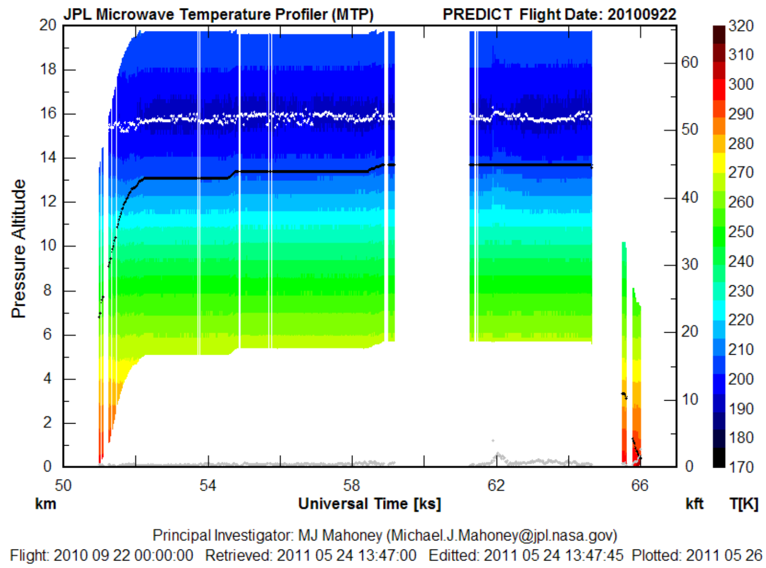


Figure 22: CTC Plot from Research Flight 22 on September 22, 2010

1.27 RF23

St Croix local flight (Figure 23). Frequency collapse to Ch1 from 54.3 - 55.9 ks. Did single channel retrieval during this period.

Data from ~55-58 ks is suspect because of interference but the tropopause retrieval appears to be okay

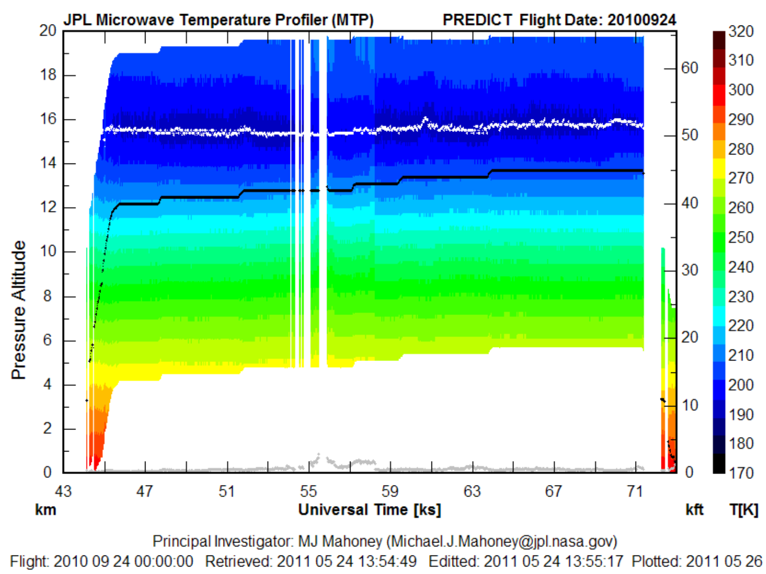


Figure 23: CTC Plot from Research Flight 23 on September 24, 2010

1.28 RF24

St Croix local flight (Figure 24). -Frequency collapse to Ch2 from 46.2 - 47.4 ks. Did single channel retrieval during this period. -Frequency collapse to Ch1 from 51.5 - 52.3 ks. Did single channel retrieval during this period. -Frequency collapse to Ch1 from 55.7 - 56.8 ks. Did single channel retrieval during this period.

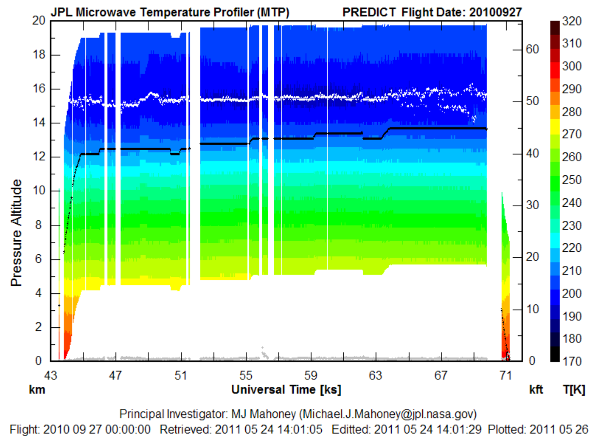


Figure 24: CTC Plot from Research Flight 24 on September 27, 2010

1.29 RF25

St Croix local flight (Figure 25). -Frequency collapse to Ch1 from 46.9 - 47.3 ks. Did single channel retrieval during this period.

-Frequency collapse to Ch3 from 49.9 - 50.5 ks. Did single channel retrieval during this period.
-Frequency collapse to Ch3 from 50.9 - 51.5 ks. Did single channel retrieval during this period.
-Frequency collapse to Ch1 from 57.4 - 58.5 ks. Did single channel retrieval during this period.
-Frequency collapse to Ch1 from 62.3 - 62.9 ks. Did single channel retrieval during this period.
-As can be seen from the MRI, the retrievals from 51-53 ks are suspect. Appears to be interference.

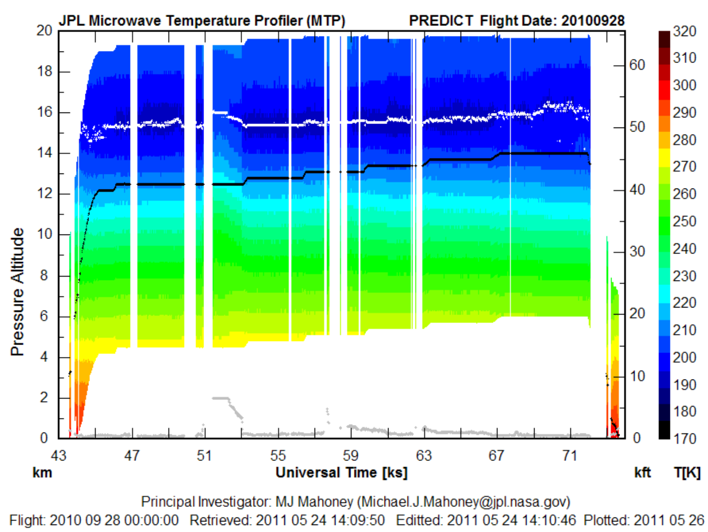


Figure 25: CTC Plot from Research Flight 25 on September 28, 2010

1.30 RF26

St Croix local flight (Figure 26). Frequency collapse to Ch3 from 52.1 - 53.0 ks. Did single channel retrieval during this period.

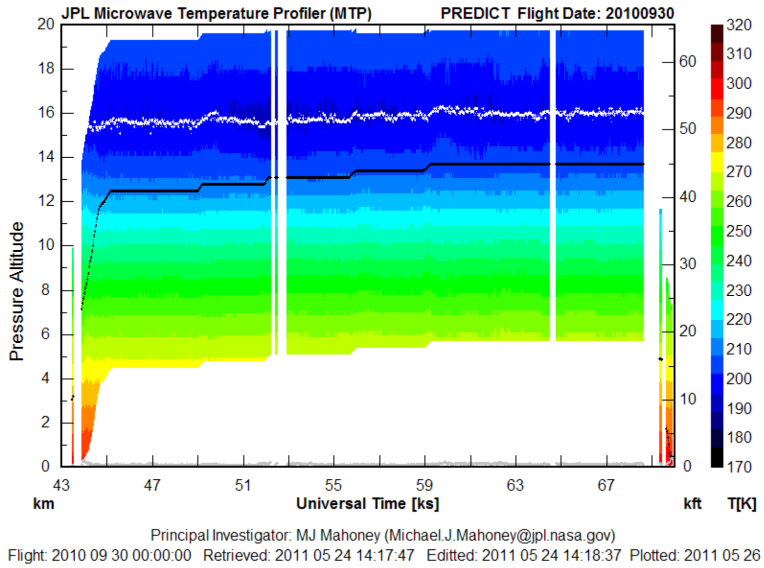


Figure 26: CTC Plot from Research Flight 26 on September 30, 2010

1.31 FF04

Ferry flight from St Croix to RMMA on October 2, 2010

2 PREDICT Temperature Calibration

2.1 Background

For nearly two decades the MTP team has been refining techniques for calibrating *in situ* temperature measurements made aboard research aircraft using radiosondes launched near the aircraft's flight track. Initially this was done by hand, and could involve as much as a day for a single comparison because of the tedious quality control procedures that had to be implemented (such as limiting pressure altitude excursions during the comparisons, restricting allowable pitch and roll changes, and checking for radiosonde temporal and spatial variability). About a decade ago these procedures were largely automated, but the comparisons were made for the entire MTP-retrieved temperature profile at that time, not just at flight level.

Even though the MTP did not participate in the T-Rex campaign, we were asked if the MTP temperature calibration techniques could be applied to the the research and avionics temperatures measured during T-Rex so that differences in these temperatures could be resolved. During T-Rex the GV flew from RMMA to near Independence, CA, where it spent most of its flight time. In addition to the NWS soundings on transit, Leeds University frequently launched radiosondes from Independence, CA (INCA), so we had a wealth of soundings with which to do comparisons. All of the radiosondes used had an accuracy of ±0.3 K. As described on another web page, we found that both the research temperature Tres (ATRL) and the avionics temperature Tavi (AT_A) had substantial warm biases with respect to radiosondes launched near the GV flight track ($Tavi - Traob = 1.21 \pm 0.12$, and $Tres - Traob = 2.37 \pm 0.12$, respectively). While Tres has the largest warm bias, we also found that the Tavi warm bias is very significantly pressure altitude dependent.

This work to understand the T-Rex *in situ* temperatures opened the door to a new approach for doing the MTP temperature calibration. As mentioned above we had previously compared the entire retrieved temperature profile to radiosondes, not just the flight level temperature. This often required several retrieval iterations through all the flights to achieve acceptable results. It was realized that if the flight level temperature was calibrated independently of the MTP data that less work would be needed. (This is the case because previously we applied a correction to the *in situ* temperature measurement called OATnavCOR. Therefore, every time OATnavCOR changed we would have to recalculate the instrument gain. If the flight level temperature is accurately calibrated from the start, then OATnavCOR is always 0.0 K, and the instrument gains do not have to be recalculated. This saves a lot of effort.)

We have continued to refine the temperature calibration techniques that we developed for T-Rex on subsequent GV campaigns. Other documents that describe this procedure can be found under 'Documentation' in the following data archives: START-08, T-REX HIPPO-1, HIPPO-2, and HIPPO-3. Before discussing the calibration procedure for the PREDICT field campaign, we will first provide a little background. During the HIPPO field campaigns the GV was for the most part continuously profiling the troposphere (and sometimes the lower stratosphere). This was a significant concern for a number of reasons:

- First, in order to obtain good temperature profile retrievals, the MTP requires that the pressure altitude of the aircraft be relatively constant during the course of a ~20 second scan. This was blatantly not the case when the GV is behaving like an atmospheric yoyo.
- Second, related to this is the fact that we have typically averaged 3 -7 scans to beat down noise introduced by mesoscale temperature variations. Such averaging would be impossible during rapid descents and ascents.
- Third, in the past we have flatly refused to do radiosonde comparisons in the troposphere because of the high lapse rate, and therefore sensitivity to altitude excursions.
- Fourth, in order to do radiosondes comparisons, you need radiosondes. Since most of the HIPPO flights were in radiosonde sparse regions (the Arctic, Antarctic and Pacific Ocean), obtaining enough comparisons to achieve good statistics would be difficult.
- Fifth, careful consideration needs to be given to the dependence of the temperature recovery factor on Mach Number. There is no way that a constant temperature recovery factor can be used when an aircraft (and its *in situ* temperature probes) are profiling the atmosphere.

For these reasons our hand was forced. Normally when we do radiosonde comparisons, we do them at the time of great-circle closest approach to the radiosonde launch site. We are also careful to make sure that no one radiosonde comparison overly weights the statistics. For example, suppose that the GV was taking off or landing at an airfield where radiosondes were launched. The "closest approach" algorithm might produce multiple times of closest approach during frequent turns. We would edit out these additional comparisons to avoid overly weighting the statistics to this site. Given the sparsity of oceanic and polar radiosondes, and the desire to have good statistics, we decided to try a new approach for the HIPPO campaigns (and other campaigns where atmospheric profiling is common). Instead of using the great-circle time of closest approach to make the comparison, we decided to do comparisons every 2 km in altitude from 2 km on up with the closest radiosonde launch site that was available. (If the closest radiosonde launch site was very distant, we had a filter that would exclude soundings beyond a specified distance threshold.) This approach would increase the number of potential comparisons by nearly an order of magnitude. But equally as important, it would allow us to assess whether any of the in situ temperature measurements had a pressure altitude dependence, which, as we remarked above, was the case for the avionics temperature during T-Rex. In addition to allowing tropospheric radiosonde comparisons, we would also be forced to abandon averaging of scans to beat down the mesoscale temperature noise, since (when profiling) the temperature change due to altitude change completely dominates any change due to mesoscale temperature variations.

2.2 PREDICT Specifics

Compared to the HIPPO field campaigns, PREDICT was benign because there was no atmospheric profiling. However, since we got more potential comparisons when doing them every 2 km in altitude (rather than only the time of closest approach) we chose the same approach as for the HIPPO campaigns.

For PREDICT there were five in situ temperature measurements that were available for radiosondes comparisons: AT_A, ATHL1, ATHL2, ATHR1, and ATHR2. (The fast response temperature ATFR was not used – apparently because it ices up.) When we analyzed the data for HIPPO-1, we initially attempted to do a correction to the in situ temperatures as a function of pressure altitude. However, since the correction from total temperature (Tt) to static temperature (Ts) involves Mach Number squared (see this web page for more information, this equation ignores the recovery factor):

$$\frac{T_r}{T_s} = 1 + r\frac{\gamma - 1}{2}M^2 \tag{1}$$

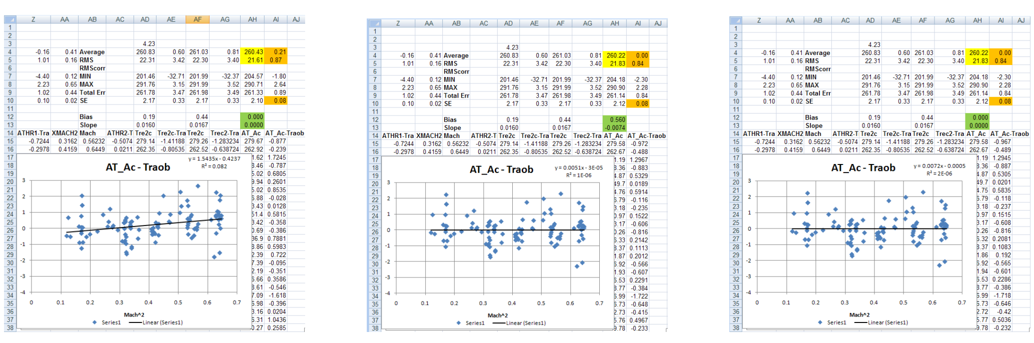
and the MTP data processing software did not use Mach Number, we needed to create a proxy for Mach Number as a function of pressure altitude Zp. We did this for a segment of a HIPPO-1 flight on 20090109, and obtained:

$$M^2(Zp) = 0.02089 + 0.06555Zp - 0.00122Zp^2 \tag{2}$$

This approach has some inherent error however, since there is not a one-to-one correspondence between pressure altitude and Mach Number. Therefore, when dealing with the PREDICT (and the previously completed HIPPO-2 and HIPPO-3) temperature calibrations, we decided to update the data analysis software and spreadsheets to use Mach Number squared (M2). Using Tx to represent one of the five in situ temperature measurements available for PREDICT, we plotted Tx-Traob versus M2, and found for the corrected temperatures (sub-script 'c'):

$$AT\_Ac = AT\_A * (1 - 0.0079 * M^2) + 0.51$$
$$ATHL1c = ATHL1 * (1 + 0.0140 * M^2) + 0.21$$
$$ATHL2c = ATHL2 * (1 + 0.0177 * M^2) - 0.15$$
$$ATHR1c = ATHR1 * (1 + 0.0188 * M^2) - 0.71$$
$$ATHR2c = ATHR2 * (1 + 0.0176 * M^2) - 0.41$$

The Mach Number corrections for these corrected temperature measurements are important. For example the maximum value of Mach Number squared when we made radiosonde comparisons was 0.65. If we assume a nominal temperature of 200 K at this Mach Number then the corrections in these five equations are -0.40 K, 0.07 K, 0.73 K, 0.51 K, and 0.62 K, respectively. These are significant temperature corrections, having a range of 1.13 K. Notice that Mach Number correction (the coefficient of M^2) is larger for the four research temperatures, compared to the avionics temperature (AT_A), which has the opposite sign. Although ATHL1 had the smallest temperature correction (0.07 K) for M^2= 0.65, AT_A had the smallest standard error (0.08 K compared to 0.34, 0.33, 0.09 and 0.28 K for the research temperatures). For these and other reasons, we adopted the corrected AT_A (that is, AT_Ac) as the *in situ* temperature to be used for PREDICT to calibrate the MTP gain.



(a) (b) (c)

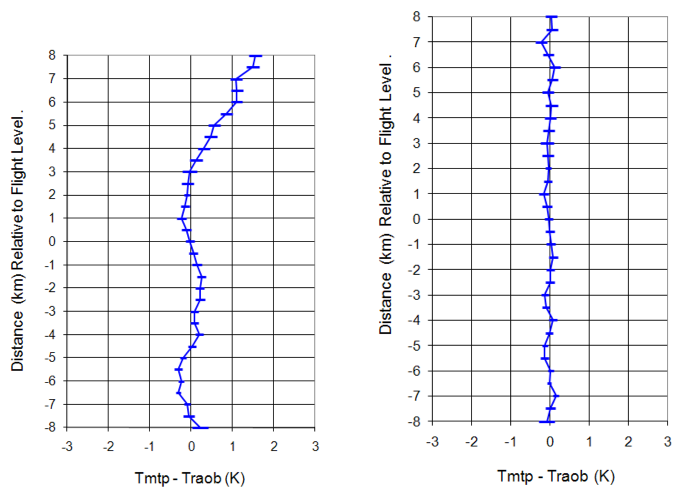
Figure 27: One hundred and seven radiosonde comparisons (a) WITHOUT a Mach Number correction; (b) WITH a Mach Number correction. The green cells show the bias and slope of the Mach Number correction; and (c) with a Mach Number correction applied in the analysis code to verify the correction. Note that the bias and slope of the Mach Number correction is zero (green cells).

Because we did radiosonde comparisons every 2 km from 2 km on up whenever the GV made a descent and ascent, we ended up with 219 potential comparisons within a range of 260 km of the aircraft. After these were edited for the criteria discussed above, including non-redundancy, the total number of comparisons was reduced to 107. Figure 27a shows these 107 comparisons without a Mach Number correction, Figure 27b shows the same comparisons with a bias correction of +0.56 K and a slope correction of -0.0074, and Figure 27c just verifies that when the corrections were applied in the data analysis software that the bias and slope corrections go to zero. Note the 'slope correction' is really pressure altitude correction, but it is more closely tied to Mach Number Squared than it is to pressure altitude.

With the corrected avionics temperature (AT_Ac) in hand, we could calculate the MTP instrument gains for each observing frequency in Counts/Kelvin as:

$$G = [Counts(Horizon) - Counts(Target)]/[AT\_Ac - T_{target}] \quad (3)$$

where Counts (Horizon) and Counts (Target) are just the output of MTP when looking at the horizon (i.e., an *in situ* measurement in front of the GV) and the reference target. (The gain calculation is actually not this simple, but we'll spare you the details!) With the gains in hand, we could now do retrievals. After the first pass through all the flights, we calculate what we call a Window Correction Table (WCT). These are small temperature corrections that are applied to the measured brightness temperatures to correct for scan mirror side lobes. By design the WCT is always 0.0 K when the scan mirror elevation angle is zero, so this does not affect the flight level temperature calibration. Another retrieval pass is now made through all the flights with the WCT applied.



(a) (b)

Figure 28: MTP Accuracy with respect to flight level: (a) assessment of MTP performance relative to radiosondes BEFORE RAF correction; (b) assessment of MTP performance relative to radiosondes AFTER RAF correction.

At this point we assess the accuracy of the MTP retrievals at all retrieval altitudes, not just flight level. This is done in Figure 28. In Figure 28a we show the MTP accuracy with respect to flight level for the 107 radiosonde comparisons. The retrieved MTP temperatures below the aircraft are relatively well behaved; however, starting at about 3 km above the aircraft a warm bias starts to develop, and it increases with altitude. Given the season and location of the PREDICT flights, the MTP overestimates the temperature above the aircraft when flying below the tropopause (which it always did) because the degraded vertical resolution is not able to resolve any sharp thermal structure which occurs in the sub-tropics. Since we understand the cause of this bias, we apply what we call the RAF-correction to the data (this stands for REF-file After Fix). It is simply a sixth-order polynomial fit to determine the correction that gives the smallest overall bias with respect to radiosondes. This is shown in Figure 28b. This is without question the very best MTP performance that has been achieved in 25 years of MTP research.